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BALLISTIC VULNERABILITY OF BORON/EPOXY DOUBLE-WALL DRIVE SHAFTS

By

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Frank N. Veit

October 1971

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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SIKORSKY AIRCRAFT DIVISION

UNITED AIRCRAFT CORPORATION

STRATFORD, CONNECTICUT

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13. ABSTRACT

This contract was initiated to assess the ballistic tolerance of boron/epoxy sandwich drive shafts.

Seven boron/epoxy double-wall shafts were ballistically impacted while under torque loads ranging from 7,500 to 12,300 in.-lb. Projectile velocities ranged from 1,540 to 2,500 fps. Static residual strength tests were then conducted. Three aluminum shafts were tested similarly for comparison.

The residual strength of the boron/epoxy shafts was approximately 8,000 in.-lb, which is about one-third the ultimate strength of an undamaged tube. The aluminum shafts exhibited residual strengths of 22,000 to 32,000 in.-lb, which would be sufficient to carry expected flight loads.

This program has shown that ±45° boron/epoxy sandwich drive shafts exhibit much lower residual strengths after ballistic damage than do the conventional aluminum shafts, and that design improvements would be required if the boron/epoxy shafts are to be acceptable in a ballistic environment.

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ballistic vulnerability						
ballistic damage						
boron/epoxy torque tube						
composite torque tube						

DEPARTMENT OF THE ARMY
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This report was prepared by Sikorsky Aircraft Division, United Aircraft Corporation, under the terms of Contract DAAJ02-71-C-0021.

The ballistic tolerance of both boron/epoxy double-wall drive shafts and conventional aluminum tail rotor drive shafts was evaluated using caliber .30 APM projectiles. The specimens were ballistically impacted under operating loads and their residual strengths determined. Four of the seven composite shafts tested failed on impact. The remaining three exhibited low residual strength. All of the aluminum tubes withstood the impact and were able to carry full operating loads with some safety factor (22,000 inch-pounds).

This Directorate concurs with the conclusions and recommendations set forth in this report.

The technical monitor for this contract was Mr. James T. Robinson, Safety and Survivability Division.

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By

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Prepared by

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Stratford, Connecticut

for

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

This contract was initiated to assess the ballistic tolerance of boron/epoxy sandwich drive shafts.

Seven boron/epoxy double-wall drive shafts were fabricated and ballistically impacted while under torque loads ranging from 7,500 to 12,300 in.-lb. Projectile velocities ranged from 1,540 to 2,500 fps. Static residual strength tests were then conducted on the shafts remaining intact. Three aluminum shafts were tested in a similar manner for comparative purposes.

Visual inspection of the specimens after ballistic impact indicated less damage to the composite shafts than to the aluminum. The boron/epoxy shafts, however, exhibited lower residual strengths and failed at approximately 8,000 in.-lb, which is about one-third the ultimate strength of an undamaged tube of the same configuration (based on company-funded test programs). The aluminum shafts failed at residual torques of 22,000 to 32,000 in.-lb. It is noted here, however, that the ±45° sandwich configuration of the boron/epoxy specimens is not a final design, as the shaft is still in the development stage. While the ±45° plies are sufficient for static strength, additional plies at other orientations may be necessary to meet stiffness requirements for critical speed. The effect of these plies on the nominal and residual strengths would have to be determined through static and ballistic tests.

This program has shown that ±45° boron/epoxy sandwich drive shafts exhibit much lower residual strengths after ballistic damage than do the conventional aluminum shafts. The use of boron/epoxy in drive shaft applications should not be ruled out, however, as design improvements may increase the residual strength of the shafts. Such improvements may include the use of multiple orientations of plies to reduce stress concentrations, reinforcing plies to reduce the extent of damage, and/or crack stoppers to limit the crack propagation. It is concluded that design improvements would be required of the boron/epoxy double-wall drive shafts if they are to be acceptable in a ballistic environment.

FOREWORD

This summary technical report was prepared by Sikorsky Aircraft, Division of the United Aircraft Corporation, under USAAMRDL Contract DAAJ02-7 -0021 (Task 1F162205AA5201), and covers the work performed during the period of February 1971 through June 1971.

The report contains the account of the program to determine the ballistic tolerance of boron/epoxy double-wall drive shafts.

The contract was monitored by James T. Robinson of the Safety and Survivability Division, USAAMRDL.

The Sikorsky individuals who made technical contributions to the program and their areas of activity are as follows:

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INTRODUCTION

The use of advanced filamentary composites offers an appreciable reduction in the structural weight of helicopters. Under company funding, Sikorsky Aircraft has evaluated the use of boron/epoxy for tail rotor drive shafts. This component was chosen because it offers a large weight reduction with the use of high-modulus, high-strength composites and can lead to minimizing the number of parts required by designing longer shaft sections with fewer bearings.

The original development work concentrated on using $\pm 45^\circ$ boron/epoxy laminates in single-wall construction as shown in Figure 1. Single-wall tube sections were tested in pure static torsion, but the results were not as encouraging as expected when compared with metal shafts. The strength of the single-wall composite tubes was severely limited by the instability of the thin walls. The stiffened wall concept of sandwich construction then evolved. This double-wall honeycomb structure, shown in Figure 2, proved to be much stronger than both single-wall boron/epoxy and aluminum shafts. The results of the static tests are shown in Figure 3. The test results showed that boron/epoxy sandwich construction yielded a 33 percent weight saving over that of conventional aluminum shafting.

In an additional company-funded effort to reduce the weight of drive systems, a composite integral end design was developed by Sikorsky Aircraft. The integral end, shown in Figure 4, has been static torsion tested and has exhibited strengths exceeding that of long shaft sections. The use of composite integral ends increases the tube assembly weight saving to 40 percent. Further weight savings can be obtained by designing longer shaft sections with fewer bearings. The longest section tested to date is 57 inches, which is the span used on existing Sikorsky models. Longer shaft lengths, by reducing the number of bearing supports and end couplings, also reduce the vulnerability of the overall subsystem. Previous screening ballistic tests of double-wall tubes, not under load, showed little damage after impact. This observation prompted the present study to assess the effects of ballistic impacts on composite sandwich shafts under actual loading conditions.

DISCUSSION

BALLISTIC IMPACT TESTS

Ballistic impact tests were conducted on seven boron/epoxy drive shafts and three aluminum drive shafts to determine the residual strength of these structures after sustaining ballistic damage. The tests were conducted at the U.S. Army Ballistic Research Laboratories (BRL), Aberdeen, Maryland, where the following test fixtures and materials were supplied:

(a) the ballistic test rig with all shaft mounting hardware
(b) ammunition (0.30 caliber - ball type)
(c) instrumentation to measure impact velocity
(d) ballistic facilities, including
  (1) capability to tumble rounds
  (2) dry nitrogen for torque application (253 cu ft at 2200 psi)
(e) personnel to conduct ballistic tests

A schematic of the loading system is shown in Figure 5. The equipment and test specimens supplied by Sikorsky Aircraft included the following:

(a) 3 surplus aluminum shafts
(b) 6 boron/epoxy drive shafts, L = 19.125 in., 4-ply outer wall, 2-ply inner wall, 0.010-in. honeycomb core, nominal diameter = 3 in., nominal ply thickness = 0.0052 in.
(c) 1 boron/epoxy drive shaft, L = 45.9 in., cross section same as above tube
(d) 3 conventional aluminum drive shafts, L = 14.625 in., 2024 T3 aluminum, OD = 3.18 in., t = .115 in.
(e) adapters and associated hardware as required

NOTE: One short boron/epoxy shaft was proof-loaded at Sikorsky to 16,350 in.-lb, to insure the structural integrity of the end attachment.

The first series of tests was conducted on March 29, 1971 at BRL in Aberdeen The initial work consisted of four firings at the surplus aluminum shafts to determine the ballistic characteristics of the test system. The six short boron/epoxy specimens were then tested with the results and test data shown in Table I, specimens 1 through 6. The ballistic tests consisted of firing at the shafts under predetermined torque load. The specimens were then to be returned to Sikorsky Aircraft for static testing to determine their residual strengths. It was planned to load the specimens to the limit design torque of 16,350 in.-lb, but a system calibration error resulted in loading the first tube to only

12,300 in.-lb. Since this specimen failed on impact, the torque was lowered to 8,200 in.-lb for the second test. Again the specimen failed on impact. For the third test, the velocity of the projectile was lowered and the shot was straight rather than tumbled as in the first two tests, but failure on impact still occurred. It was apparent that both the torque and velocity of impact influenced the tests, and consequently the remaining three shafts were tested at reduced load and velocity as shown in Table I. These shafts did not fail on impact and were returned to Sikorsky Aircraft for static residual strength tests.

The second series of tests was conducted at BRL on May 11, 1971. This series included recalibration of the loading system and ballistic tests of one 45.9-inch boron/epoxy shaft and three 14.625-inch aluminum shafts. The results of these tests are summarized in Table I, specimens 7 through 10. The boron/epoxy shaft failed on impact under 10,000 in.-lb. All three aluminum shafts sustained the load on impact and were returned to Sikorsky Aircraft for residual strength tests.

Photographs of ballistically damaged specimens are seen in Figures 6 through 23. The shaft numbering system corresponds to that contained in Table I. An investigation of the tubes indicates that the actual damaged area is less on the composite shafts than on the aluminum shafts. This can be seen by examining Figures 11 through 23. Composite specimens 4,5, and 6, which sustained the load on impact, exhibit relatively small holes with little adjacent fiber damage. The long composite specimen also shows a small damaged area (see Figures 16 and 17). In contrast, however, the aluminum shafts have larger holes with flowering and sharp corners. In all cases the damage was greatest for tumbled shot at high velocities.

TABLE I. BALLISTIC TESTS OF DRIVE SHAFTS

	Specimen	Type of Shot	Velocity of Shot (fps)	Torque at Impact (in.-lb)	Results
1	Composite Shaft L = 19.125 in.	Tumbled	2,500	12,300	Shaft failed on impact. Shot hit tangentially in first doubler. Laminate separated at 45° except at doubler, where failure was circumferential.
2	Composite Shaft L = 19.125 in.	Tumbled	2,530	8,200	Shaft failed on impact. Shot hit tangentially about 1½ inches inboard of first doubler. Failure at 45°. Shaft separated into two pieces.
3	Composite Shaft L = 19.125 in.	Straight	2,100	10,000	Shaft failed seconds after impact under sustained load. During this period, cracking noises were heard. Failure at 45°.
4	Composite Shaft L = 19.125 in.	Straight	2,310	7,500	Shaft held load. Shot hit at 45° to the centerline. Slight delamination around entrance and exit holes.
5	Composite Shaft L = 19.125 in.	Straight	1,690	7,500	Same as #4
6	Composite Shaft L = 19.125 in.	Tumbled	1,540	7,500	Same as #4 but holes larger than for straight shot.
7	Composite Shaft L = 45.9 in.	Straight	2,260	10,000	Shaft failed on impact. Shot hit at 45° to centerline at midspan.
8	Aluminum Shaft L = 14.625 in.	Straight	2,430	10,000	Shaft held load. Flowering at exit hole.
9	Aluminum Shaft L = 14.625 in.	Straight	2,420	13,000	Shaft held load. Flowering at exit hole.
10	Aluminum Shaft L = 14.625 in.	Tumbled	2,420	16,350	Shaft held load. Flowering at exit hole. Holes larger than for straight.

STATIC RESIDUAL STRENGTH TESTS

The residual strength tests conducted at Sikorsky Aircraft were static torsion tests. The specimens were mounted between two flat steel plates, and the load was applied by rotating one plate with respect to the other by means of a hydraulic pump. The steel plates were splined to allow longitudinal motion of the shafts upon being torqued. All specimens that survived the ballistic tests were loaded to failure in this manner, and the results are shown in Table II. Composite specimens 1, 2, 3 and 7 failed on ballistic impact. The remaining three composite shafts and the three aluminum shafts yielded results indicating that the aluminum shafts have approximately three times the residual strength as the composites.

The failures in the residual strength tests of the composite shafts were similar to those that occurred on impact. The brittle nature of the composite caused catastrophic failures, with the specimens breaking along a 45° angle. Cracking noises were heard at 1000 in.-lb before failure. The aluminum shafts also failed along angles approximately 45° to the shaft axis. In the case of the aluminum shafts, however, no noises were heard prior to failure, and the cracks did not propagate as far as in the composite shafts.

It should be noted that the maximum operating torque on the aircraft for which these shafts were designed is 16,350 in.-lb; applying a factor of 1.5, the ultimate design torque is 24,500 in.-lb. If the dynamic unbalance of the flowered aluminum shaft after ballistic damage is not severe, the aluminum shafts, with residual strengths in the range of 22,000 to 32,000 in.-lb, would be able to land safely. The present boron-epoxy shafts, however, exhibited residual strengths of less than 10,000 in.-lb and therefore would not be acceptable in a ballistic environment.

TABLE II. RESIDUAL STRENGTH TESTS

SPECIMEN		LENGTH (in.)	RESIDUAL STRENGTH (in.-lb)
1	boron/epoxy	19.125	failed
2	boron/epoxy	19.125	failed
3	boron/epoxy	19.125	failed
4	boron/epoxy	19.125	8,240
5	boron/epoxy	19.125	7,780
6	boron/epoxy	19.125	7,000
7	boron/epoxy	45.9	failed
8	aluminum	14.625	26,400
9	aluminum	14.625	32,600
10	aluminum	14.625	22,000

ANALYSIS

The strength of boron/epoxy drive shafts has been investigated in previous company-funded studies at Sikorsky Aircraft through static torsion testing of full-scale components. These tests have yielded strength data on failure shear stress as a function of length-to-diameter ratio (L/D) curves for both single-wall and double-wall (honeycomb sandwich) shafts, as seen in Figure 3. For comparison, the data for conventional aluminum shafts is also shown. It is readily seen that much higher stresses can be achieved in the sandwich tubes, permitting more efficient, lighter weight designs.

The point to be noted for this discussion of ballistic tolerance is the ultimate shear strength capability of the boron/epoxy shafts, indicated by the flat part of the curve in Figure 3. Below an L/D of approximately 3.5, the shafts fail due to material ultimate strength. Above this L/D value, torsional stability governs the failures, and the shaft capability depends on the tube geometry. It is seen in Figure 3 that the ultimate shear stress of boron/epoxy shafts ($\pm 45^{\circ}$ fiber orientation) is approximately 100,000 psi, which is consistent with theory stating that ultimate shear strength is approximately one-half ultimate tensile strength (200,000 psi for boron/epoxy). It is expected, therefore, that failure will occur when the ballistic damage produces local shear stress concentrations exceeding 100,000 psi.

The basic analytical approach used in this study was to calculate stress concentration factors (K_t) for the damaged parts and then to apply these factors to the nominal shear stresses to determine the expected failure loads. It is noted that stress concentration factors are not valid for most metal structures under the action of static loads since the plastic characteristics of the metals permit local yielding to redistribute the stresses and thereby eliminate the effect of the concentration. With boron/epoxy, however, the stress-strain relationship is very nearly linear to failure, and therefore little or no yielding can take place. It is this brittle nature of boron/epoxy that permits the use of stress concentration factors under the application of static loads.

Two different theories were used to calculate the stress concentrations, and the methods were compared. The first was to use the stress concentration factors for isotropic materials, that is, to use the published data for hollow metal shafts with holes, found in Reference 1. Upper and lower bounds on the calculated failure loads were obtained by considering the actual hole size and the equivalent hole size (area of damaged fibers) in the determination of K_t. The actual and equivalent damage areas for each specimen are shown in Table III, along with the upper and lower bounds of the calculated failure loads using isotropic theory.

The second method was to use the theory for stress concentrations around holes in infinite orthotropic plates found in Reference 2. In Reference 2 a formula was developed to calculate the stress at any point on the circumference of a circular hole in an infinite orthotropic plate as a function of the nominal shear stress. Since the plate was considered infinite, the size of the hole had no effect on the analysis, and consequently the same calculated failure torque was found for all the specimens in this program. The assumption of an infinite plate was not valid for the shaft specimens of this program, and therefore the results of this theory yielded results significantly lower than those observed experimentally, as shown in Table III.

An effort was made to reduce the stress concentration by changing the fiber orientation in the shafts. Although the orthotropic theory did not yield the true magnitudes of the stress concentrations, the theory was used to determine relative stress concentration magnitudes in shafts of different orientations. It was found that stress concentration factors were reduced by approximately fifty percent for a shaft of $\pm 60^\circ$ fiber orientation. It must be noted, however, that the torsional strength of the $\pm 60^\circ$ shaft is also lower than the $\pm 45^\circ$ shaft, and an experimental and analytical program would be required to determine what advantages would be gained by changing the fiber orientation. This work is beyond the scope of the present study.

The results of all experimental and analytical work are shown in Table III. The calculated upper and lower bounds on the residual strength using isotropic theory show fair correlation with the experimental results, giving slightly higher values than test. Specimens 1, 2, 3 and 7 failed under impact, which would be expected based on the calculated residual strengths.

The calculations using orthotropic plate theory yielded results considerably below the test values. As mentioned previously, this theory assumed an infinite plate and was therefore not valid for this application. This indicates a need for an analytical method for the determination of stress concentrations around holes in orthotropic structures of finite dimensions.

The results indicate that the damage in both the composite and metal shafts was proportional to the type of shot (tumbled or straight) and the velocity of the shot. The greatest damage was caused by tumbled shot at high velocities. In the composite shafts the damage took the form of a hole with adjacent fiber damage, while the metal shafts exhibited considerable flowering around the hole with sharp edges. In both cases, the residual strength (failure load after damage) was proportional to the extent of damage, as expected.

TABLE III. COMPARISON OF ANALYTICAL AND TEST RESULTS

SPEC.	MAT'L	TYPE OF SHOT	VELOCITY OF SHOT (fps)	TORQUE ON IMPACT (in.-lb)	DAMAGE: HOLE AREA (in.^{2})	DAMAGE: FIBER DAMAGE AREA (in.^{2})	RESIDUAL STRENGTH (in.-lb)	CALCULATED FAILURE TORQUE USING ISOTROPIC THEORY (in.-lb): FOR HOLE AREA	CALCULATED FAILURE TORQUE USING ISOTROPIC THEORY (in.-lb): FOR FIBER DAMAGE AREA	CALCULATED FAILURE TORQUE USING ORTHOTROPIC PLATE THEORY (in.-lb)
1	B/E	T	2500	12,300	.63	1.15		9200	7300	5900
2	B/E	T	2530	8,200	1.02	2.10		8500	5400	5900
3	B/E	S	2100	10,000	.13	.31		9700	9500	5900
4	B/E	S	2310	7,500	.10	.70	8,240	10000	8150	5900
5	B/E	S	1690	7,500	.10	.38	7,780	10000	9600	5900
6	B/E	T	1540	7,500	.28	.28	7,000	8400	8300	5900
7	B/E	S	2260	10,000	.20	.39		9000	8900	5900
8	Al	S	2430	10,000	.94		26,400			
9	Al	S	2420	13,000	.78		32,600			
10	Al	T	2420	16,350	1.18		22,000			

B/E = boron/epoxy

Al = Aluminum

T = Tumbled shot

S = Straight in shot

CONCLUSIONS AND RECOMMENDATIONS

The results of this program indicate that conventional aluminum drive shafts are superior to ±45° boron/epoxy double-wall shafts when ballistic damage is sustained. The plastic nature of metals permits local yielding around the damaged area, which reduces the effect of the stress concentration and allows high loads to be sustained. Boron/epoxy, however, behaves elastically up to failure and therefore is subject to stress concentration and fails at loads well below the maximum operating levels. The potential weight and stability advantages of the present composite construction and fiber orientation appear to be outweighed by its poor tolerance to ballistic damage.

Thus ballistic damage tolerance is a critical area of concern for composite drive shafts, and further analysis and test efforts are required to assure that the high-strength, high-modulus composites can be effectively used in a combat aircraft. The principal problem appears to be the high effective stress concentration experienced in the ±45° ply layup when subjected to ballistic damage. The theoretical stress concentration factors from Reference 2 indicate that ply orientation may have an appreciable effect on the magnitude of the concentration factor, and therefore it may be possible to improve the tolerance to ballistic damage by using different combinations of ply orientations. This is beyond the scope of the present study, but it remains an area for consideration in future investigations.

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1. "Stress Concentration Data," Royal Aeronautical Society Engineering Sciences Data, #65004, page 32, September 1965.

2. S. G. Lekhnitskii, "Anisotropic Plates," Gordon & Breach Science Publishers, New York, 1968.

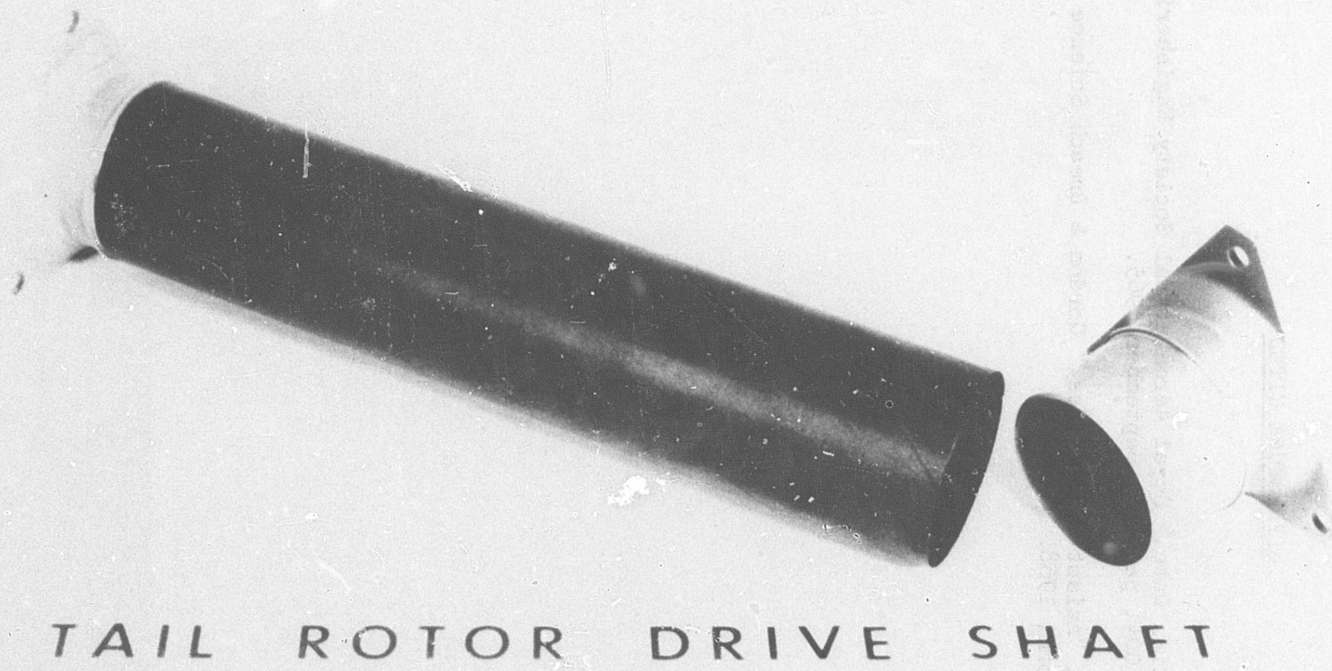


Figure 1. Boron/Epoxy Drive Shaft.

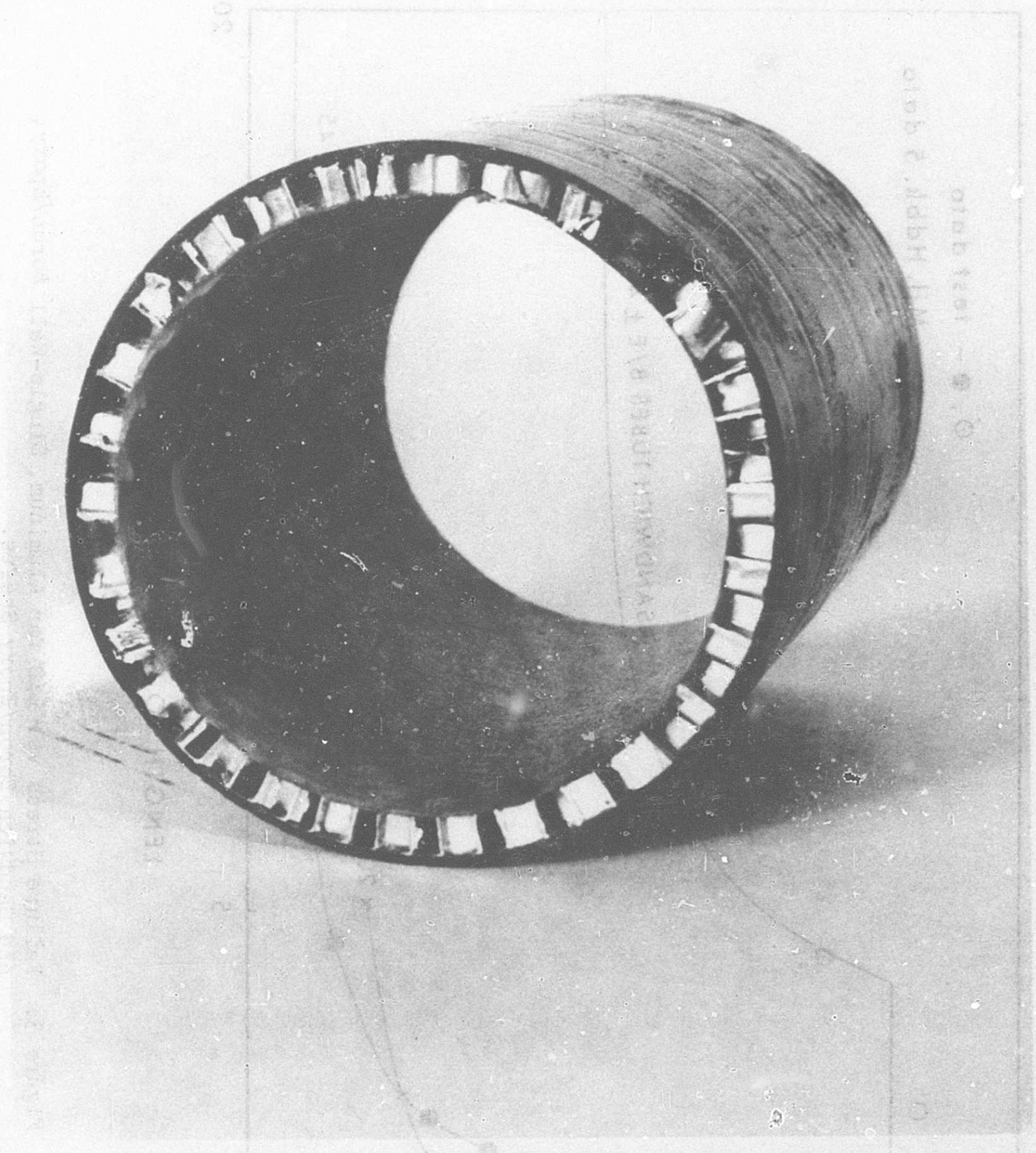


Figure 2. Composite Sandwich Tube Section.

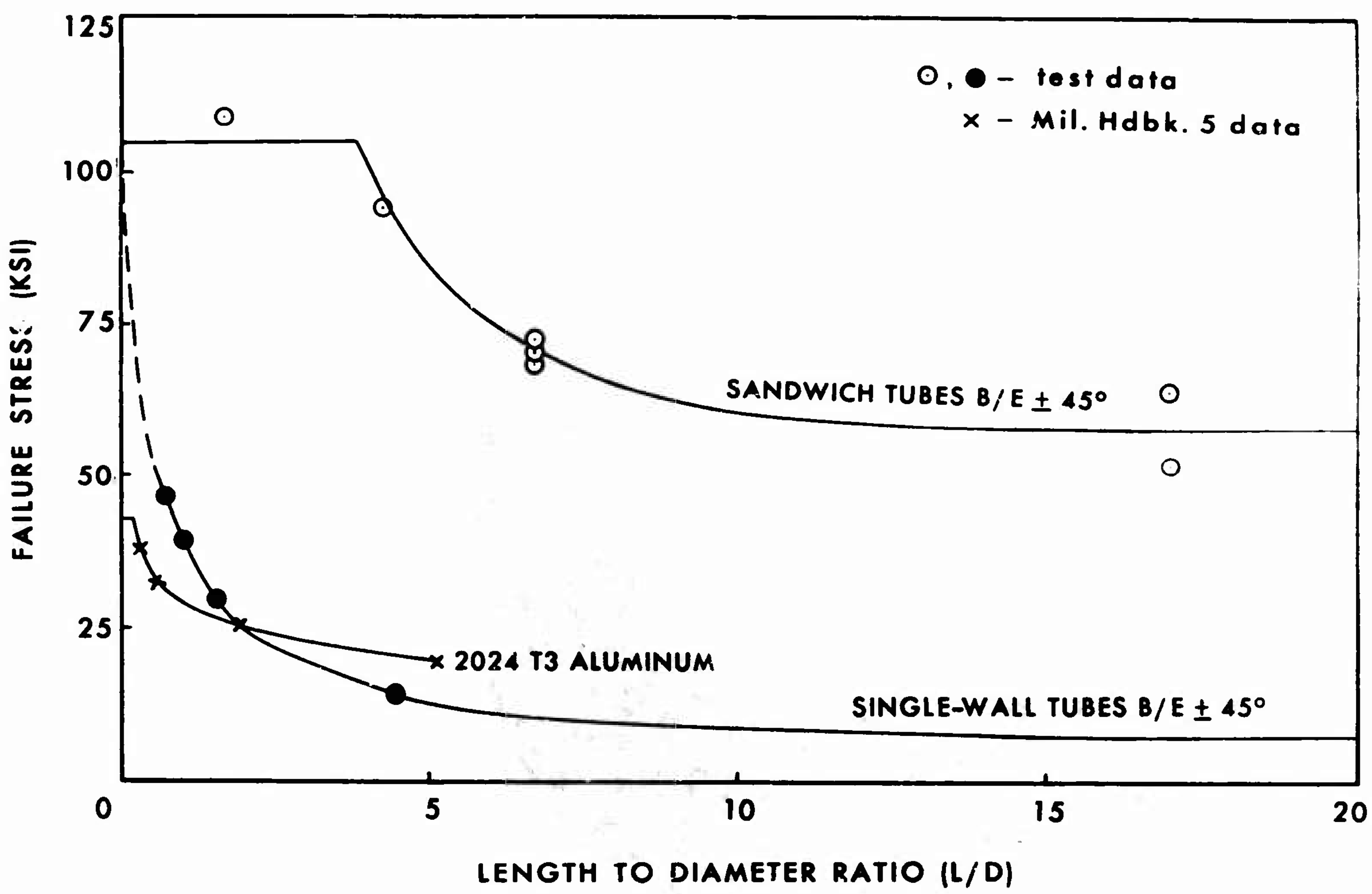


Figure 3. Failure Stress vs. L/D for Aluminum, Single-Wall Boron/Epoxy, and Sandwich Boron/Epoxy Shafts.

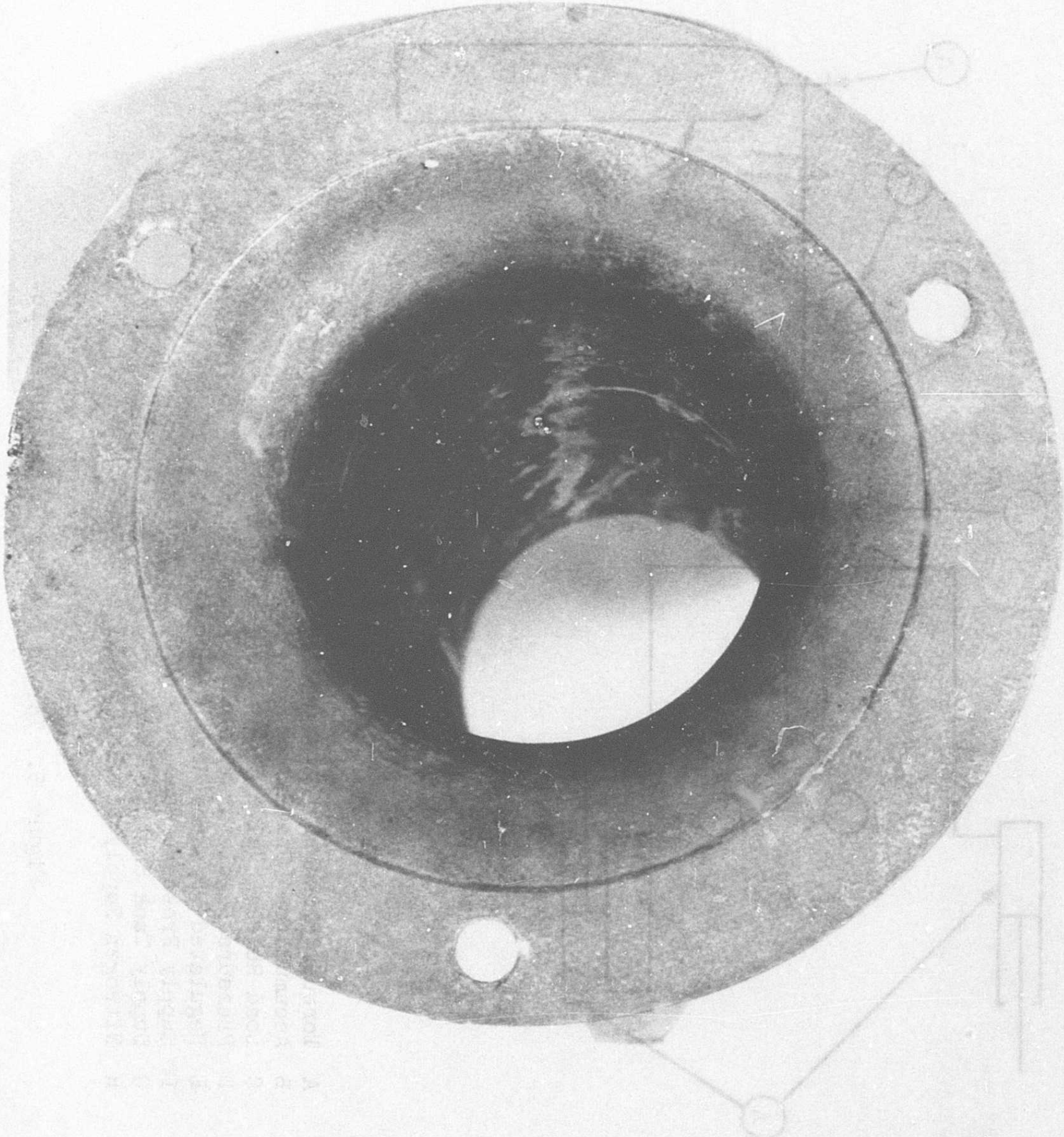
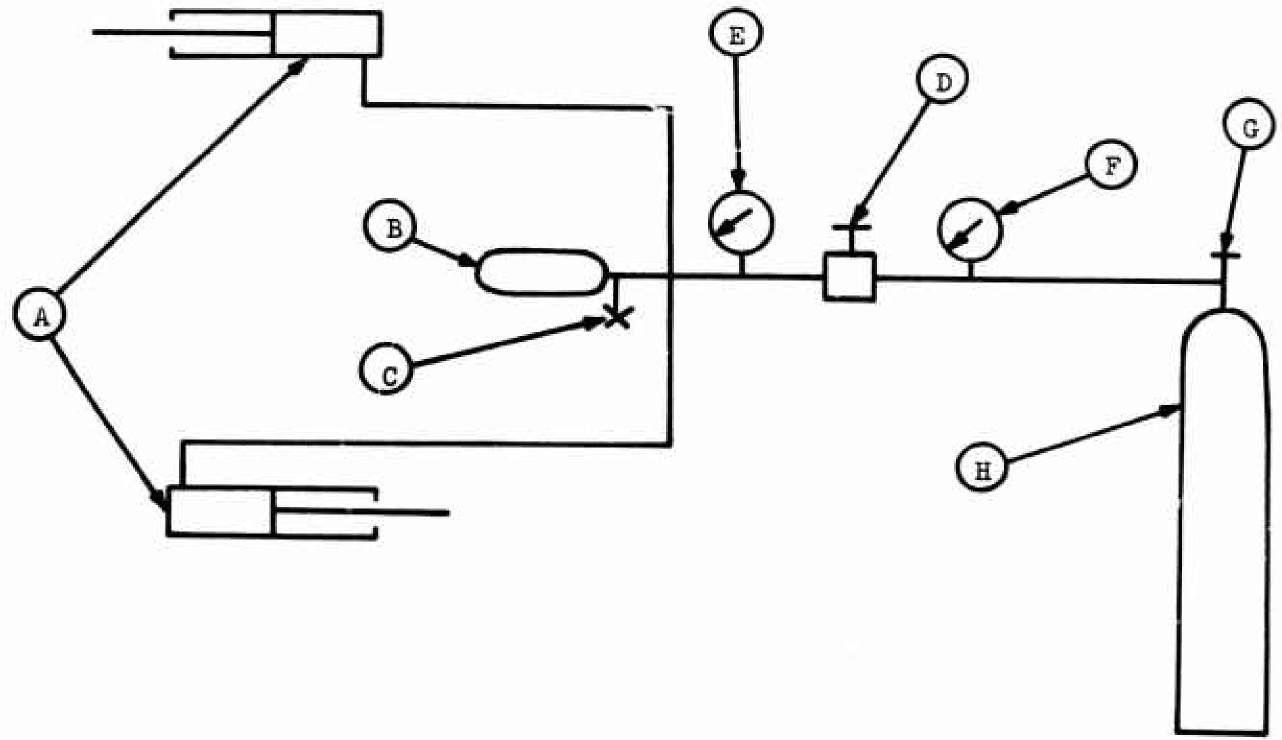


Figure 4. Composite Integral End Flange.



A Torque Cylinders (Existing Part of Test Fixture)
B Accumulator (One Gallon)
C Load Release Valve
D Pressure Regulator (0 - 1000 PSI)
E Regulated Pressure Gage (0 - 600 PSI)
F Supply Pressure Gage (0 - 3000 PSI)
G Supply Tank Shutoff Valve
H Nitrogen Supply Bottle (253 CF @ 2200 PSI)

Figure 5. Torque Loading System Schematic.

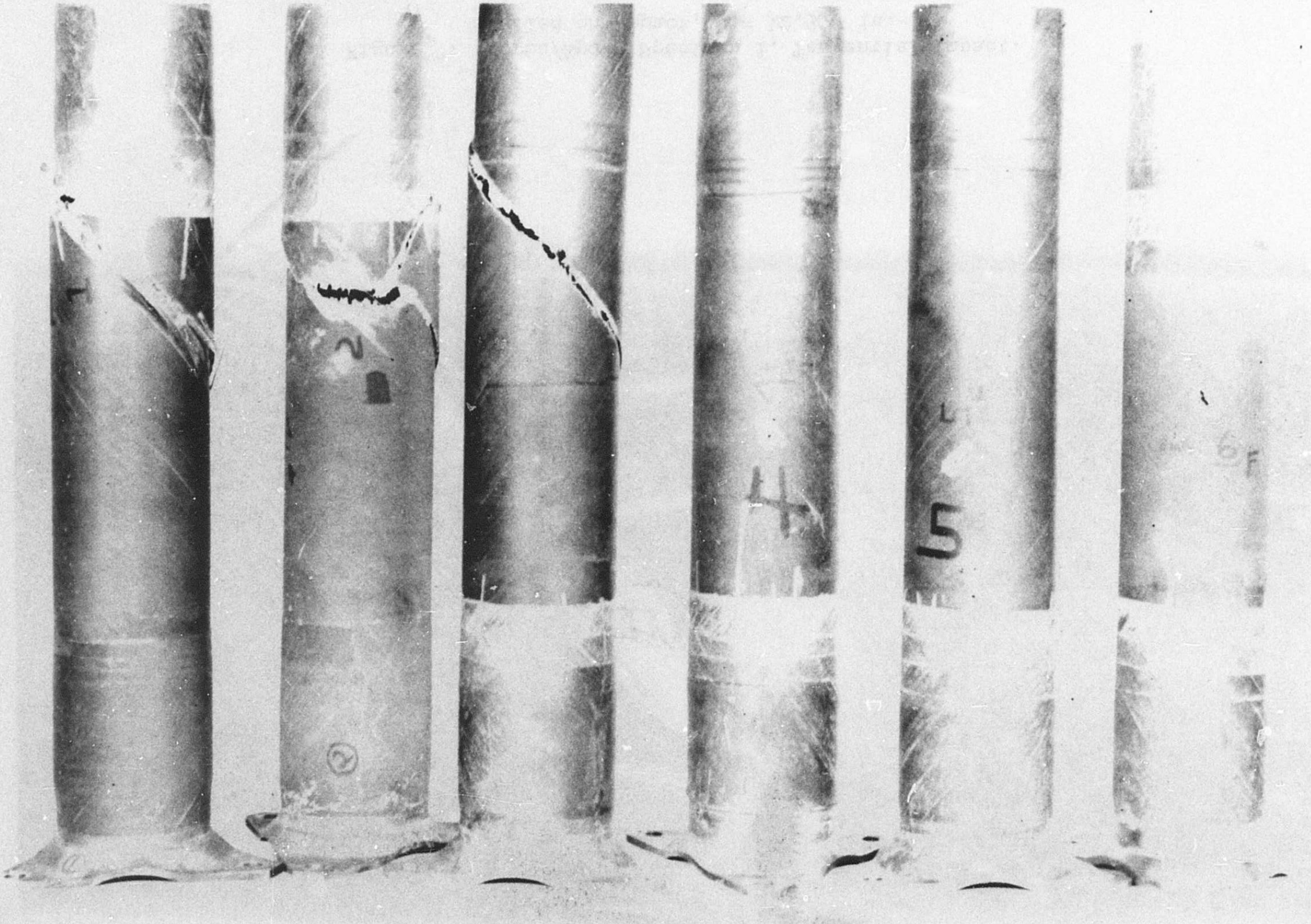


Figure 6. Composite Shafts After Ballistic Tests.

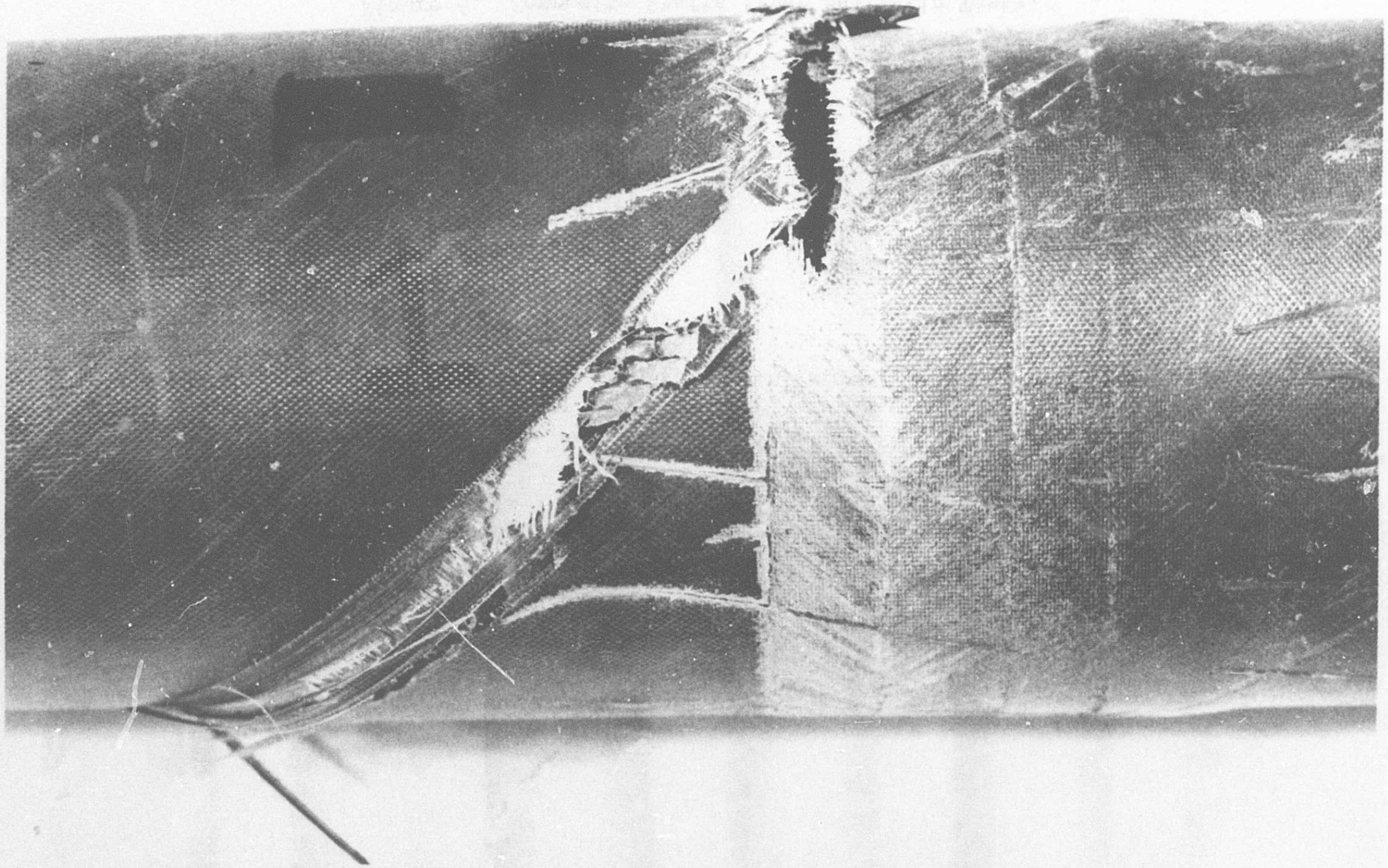


Figure 7. Boron/Epoxy Specimen 1, Tangential Impact.
Failed on Impact, T = 12,300 in.-lb.

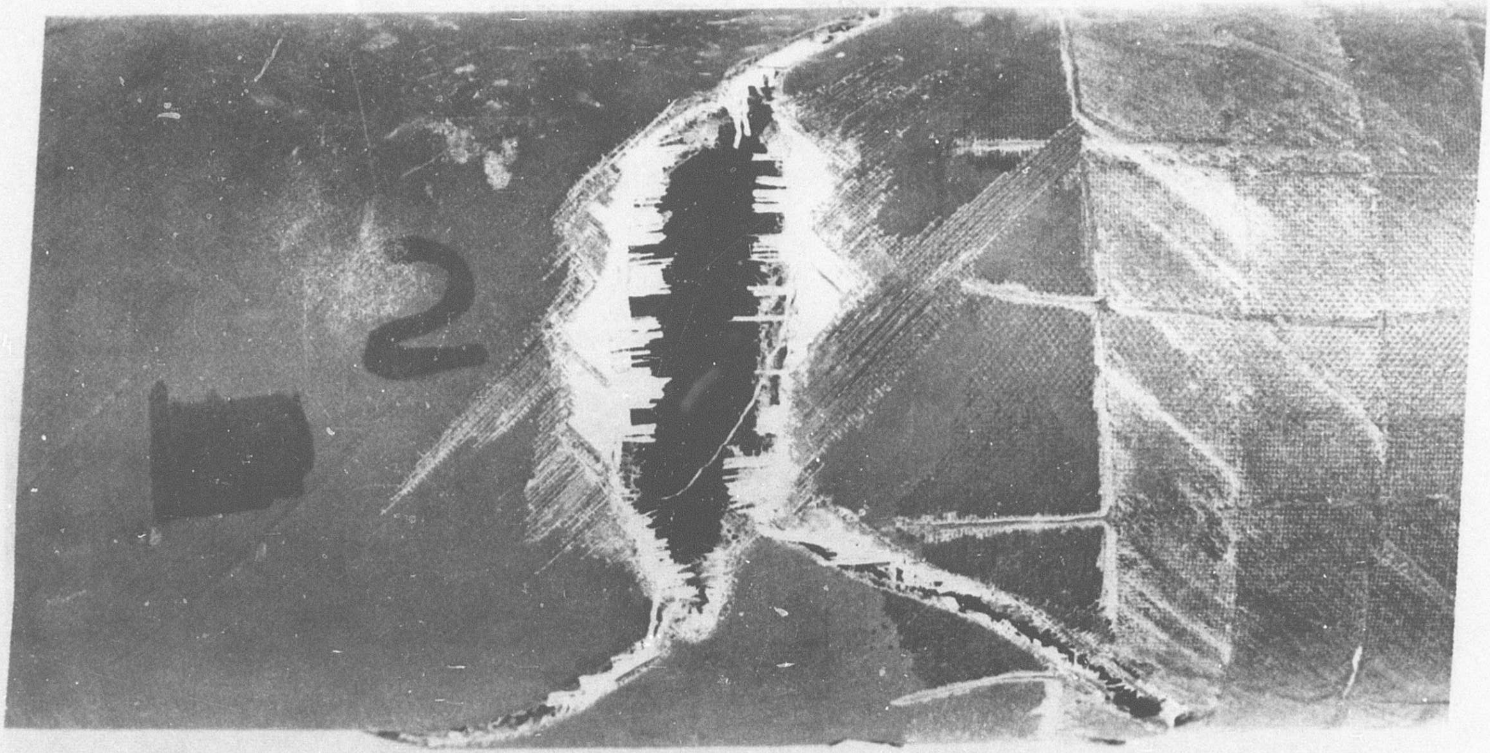


Figure 8. Boron/Epoxy Specimen 2, Tangential Impact.
Failed on Impact, T = 8,200 in.-lb.

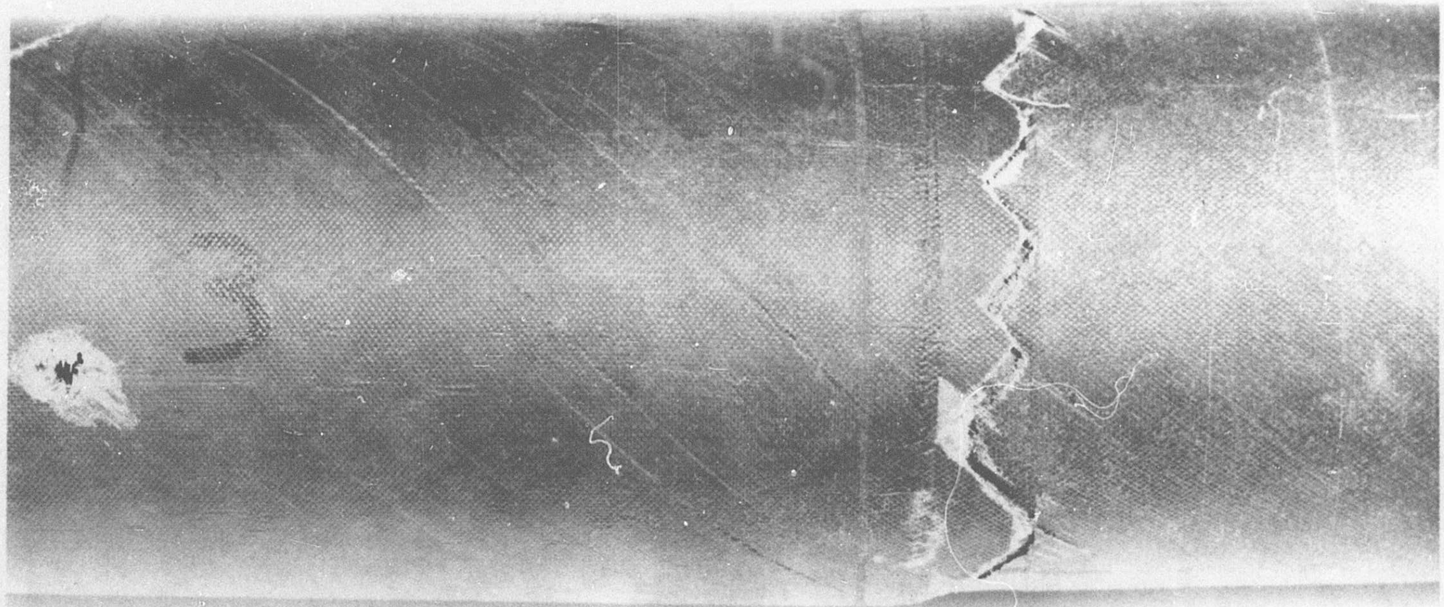


Figure 9. Boron/Epoxy Specimen 3, Entrance Hole Damage.
Failed on Impact, T = 10,000 in.-lb.

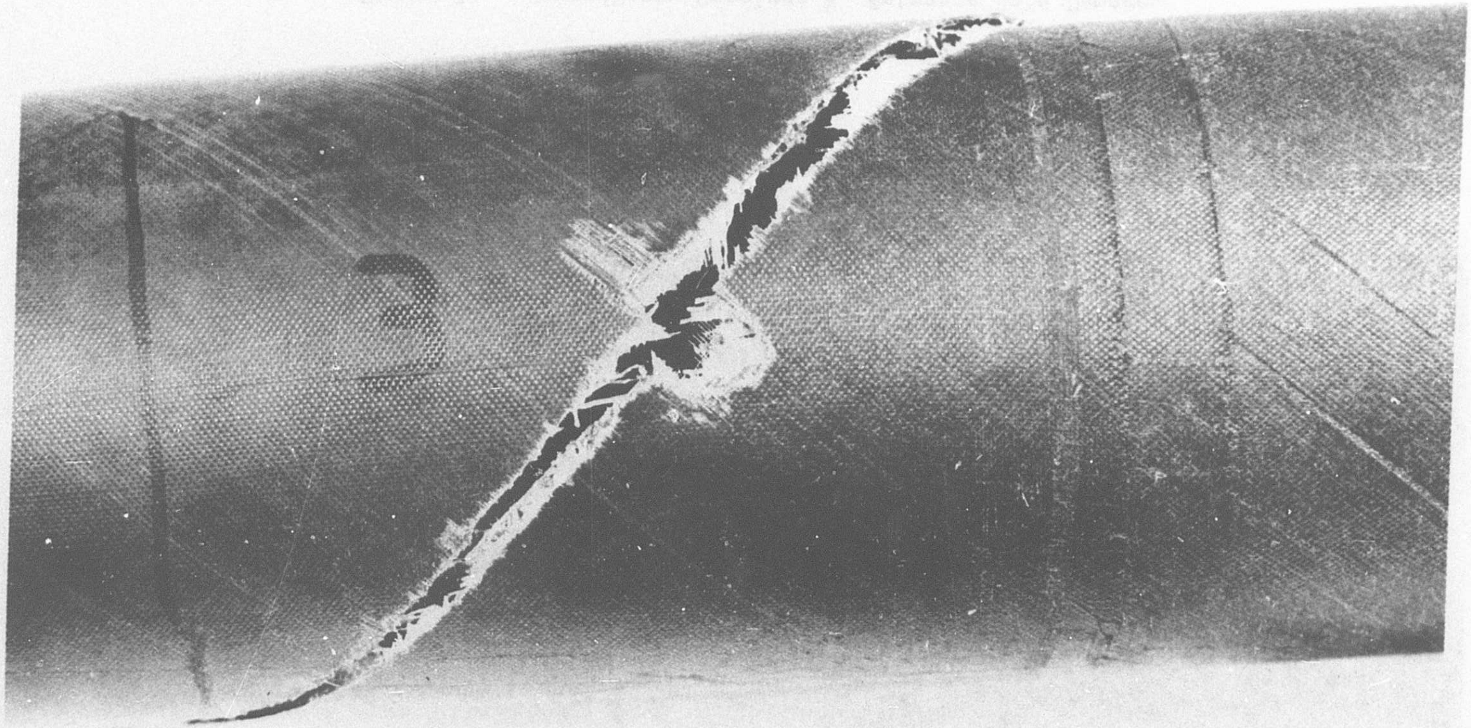


Figure 10. Boron/Epoxy Specimen 3, Exit Hole Damage. Failed on Impact, T = 10,000 in.-lb.

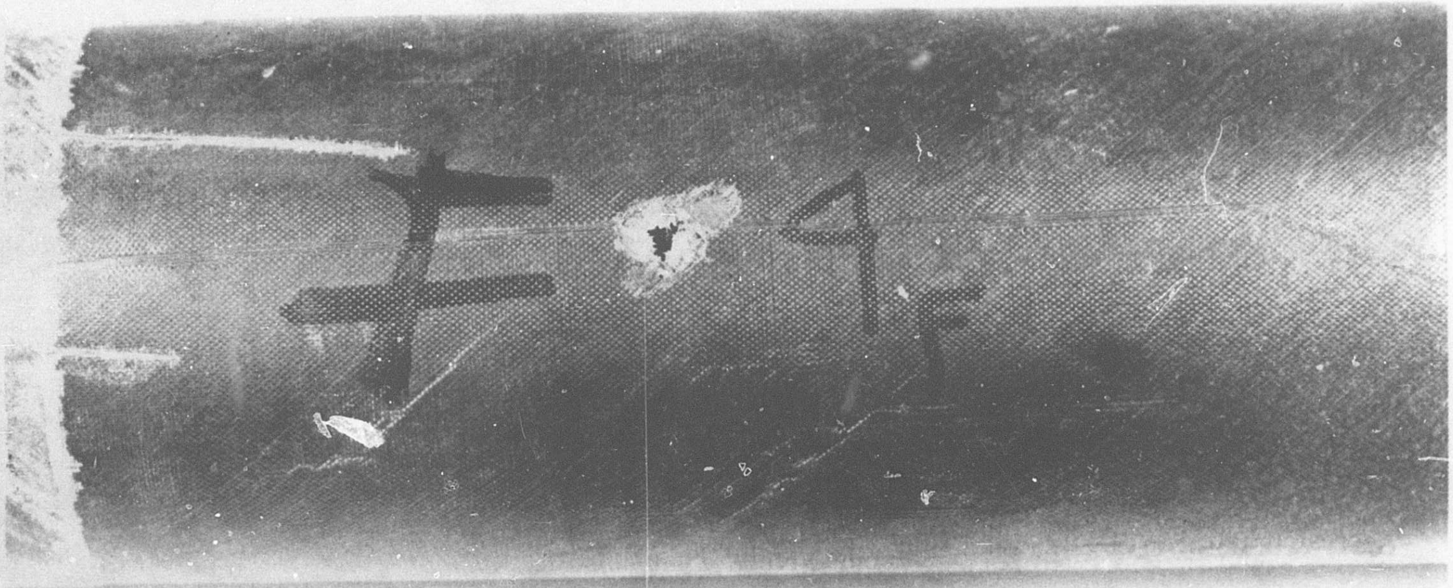


Figure 11. Boron/Epoxy Specimen 4, Entrance Hole Damage.
Torque on Impact = 7,500 in.-lb,
Residual Strength = 8,240 in.-lb.

Figure 12. Boron/Epoxy Specimen 5, Entrance Hole Damage.
Torque on Impact = 7,500 in.-lb,
Residual Strength = 7,780 in.-lb.

Figure 13. **Boron/Epoxy Specimen 5, Exit Hole Damage.**
Torque on Impact = 7,500 in.-lb,
Residual Strength = 7,780 in.-lb.

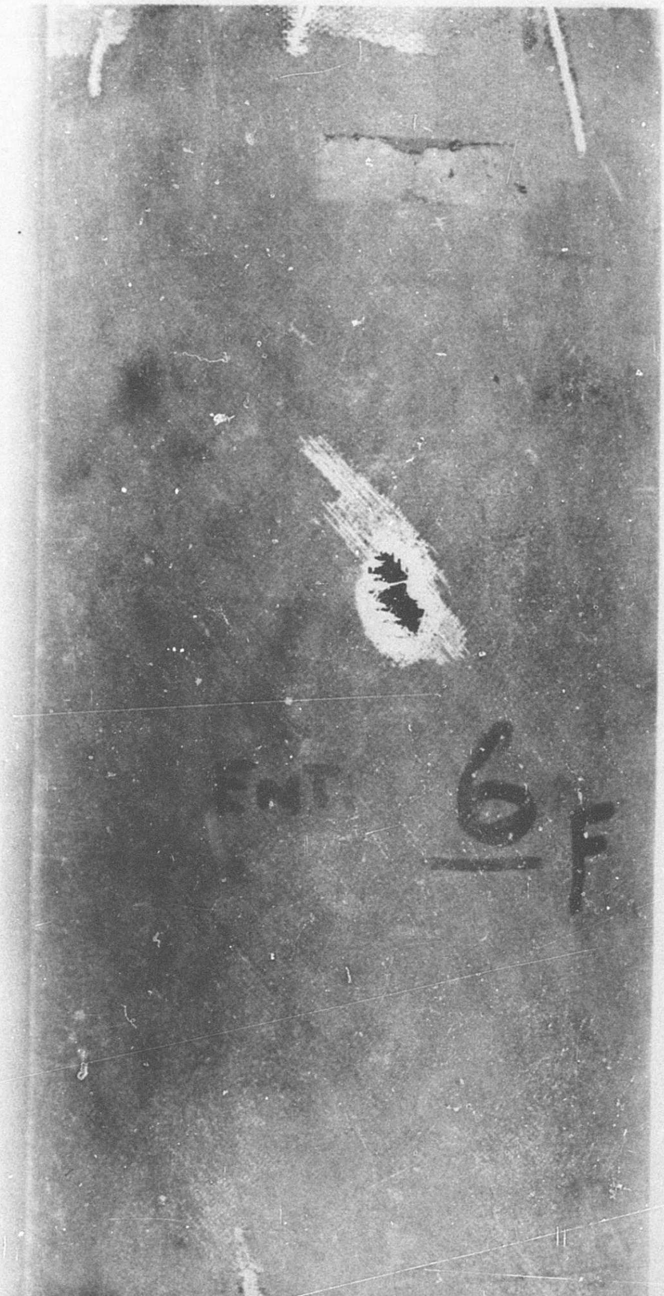


Figure 14. Boron/Epoxy Specimen 6, Entrance Hole Damage.
Torque on Impact = 7,500 in.-lb,
Residual Strength = 7,000 in.-lb.

Figure 15. Boron/Epoxy Specimen 6, Exit Hole Damage.
Torque on Impact = 7,500 in.-lb,
Residual Strength = 7,000 in.-lb.

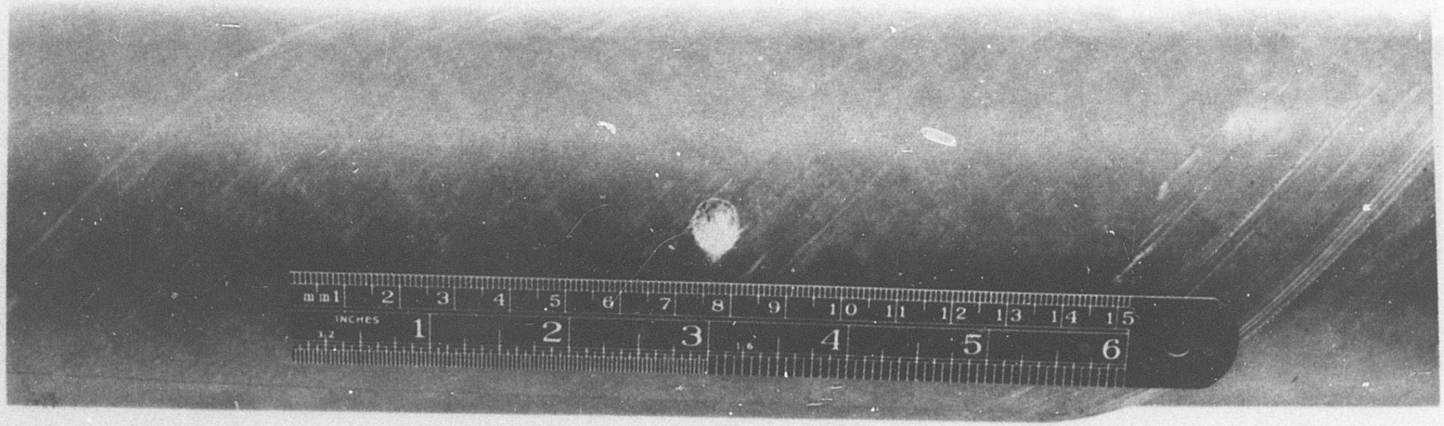


Figure 16. Boron/Epoxy Specimen 7, L = 45.9 inches, Entrance Hole Damage. Failed on Impact, T = 10,000 in.-lb.

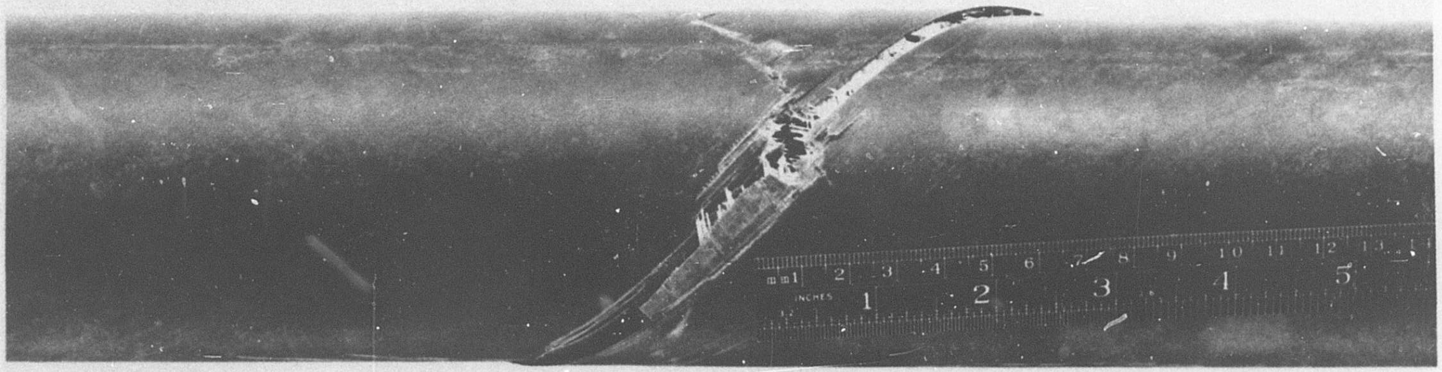


Figure 17. Boron/Epoxy Specimen 7, L = 45.9 inches, Exit Hole Damage. Failed on Impact, T = 10,000 in.-lb.

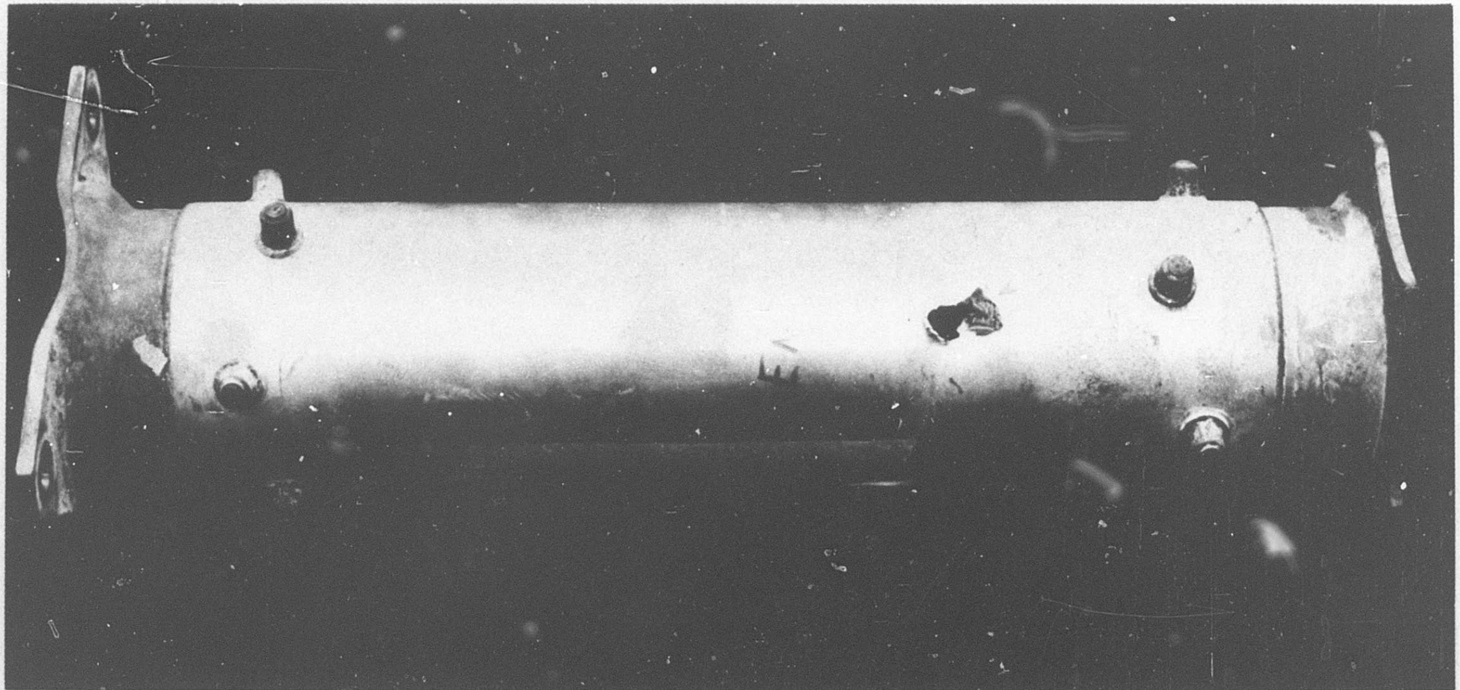


Figure 18. Aluminum Specimen 8, Entrance Hole Damage.
Torque on Impact = 10,000 in.-lb,
Residual Strength = 26,400 in.-lb.

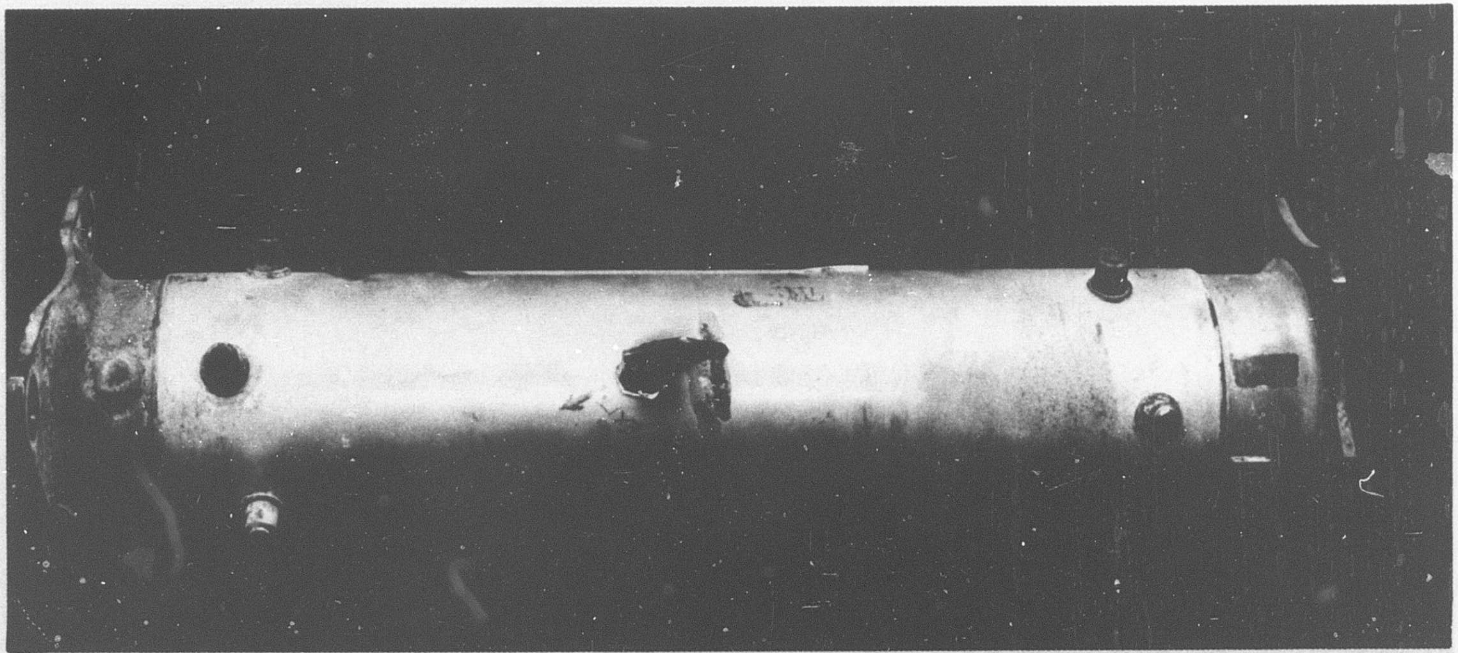


Figure 19. Aluminum Specimen 8, Exit Hole Damage.
Torque on Impact = 10,000 in.-lb,
Residual Strength = 26,400 in.-lb.

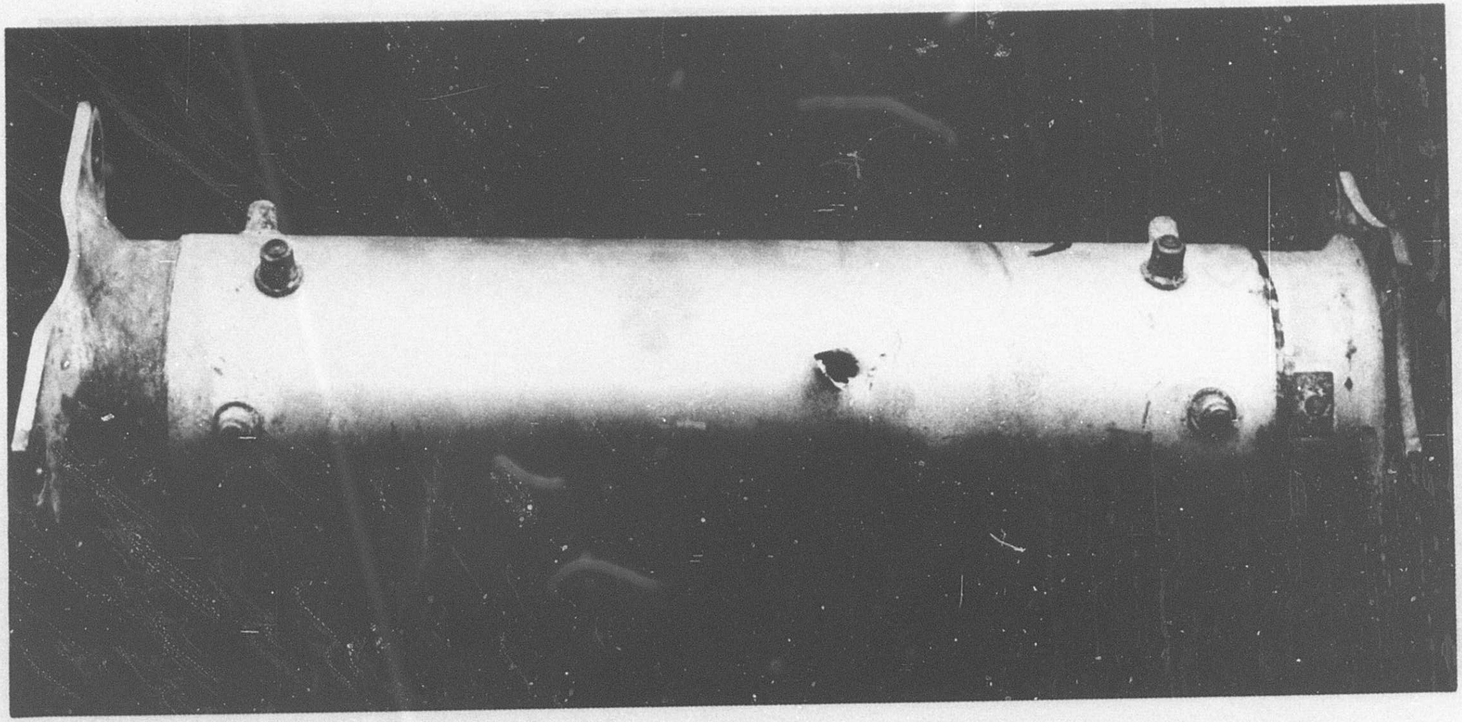


Figure 20. Aluminum Specimen 9, Entrance Hole Damage.
Torque on Impact = 13,000 in.-lb,
Residual Strength = 32,600 in.-lb.

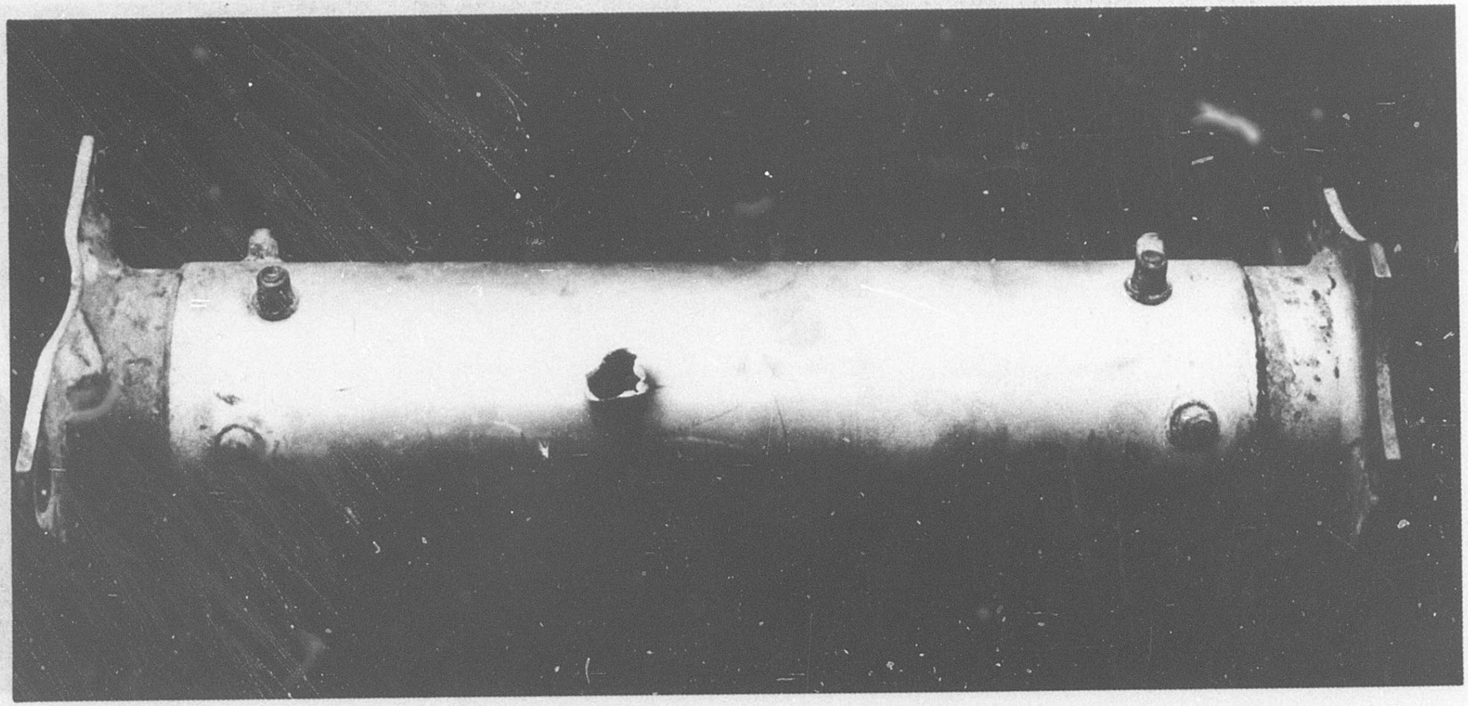


Figure 21. Aluminum Specimen 9, Exit Hole Damage.
Torque on Impact = 13,000 in.-lb,
Residual Strength = 32,600 in.-lb.

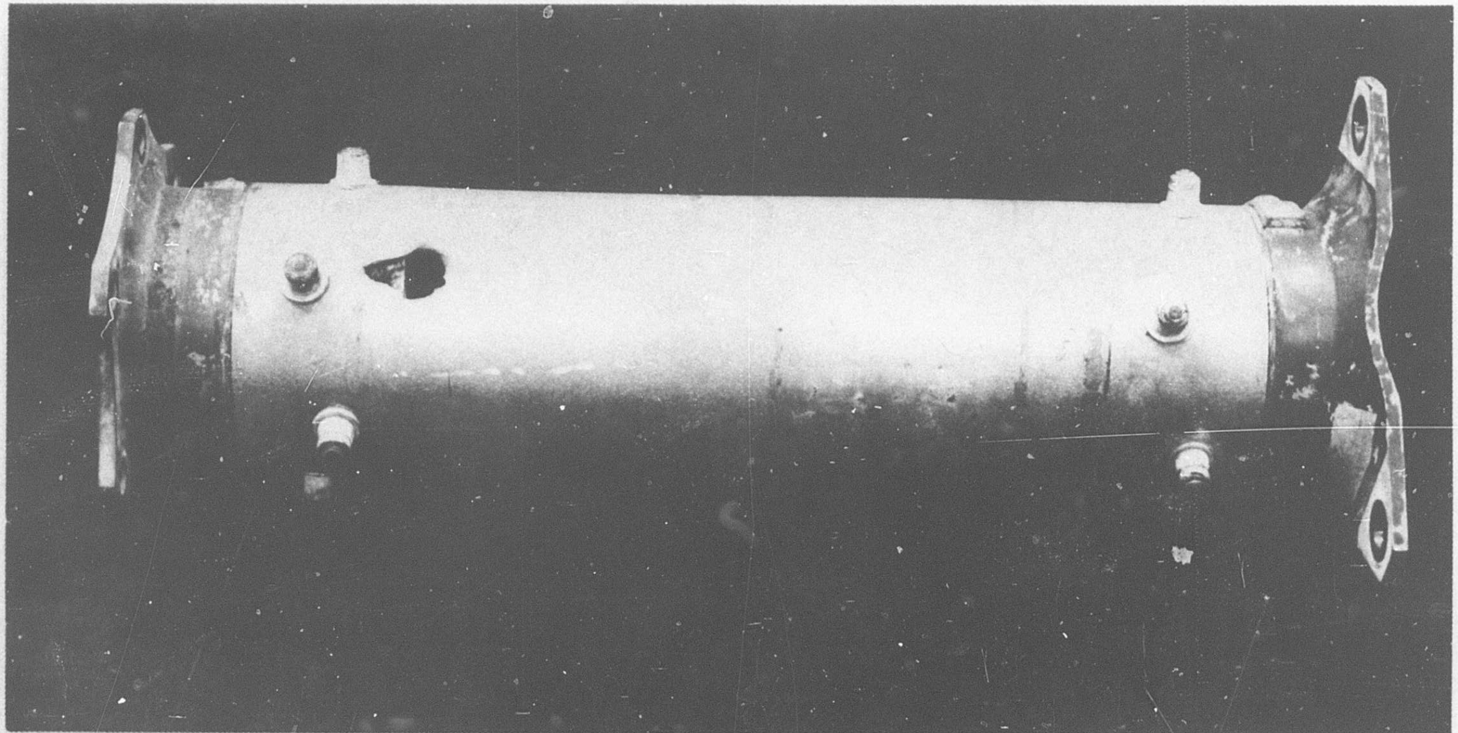


FIGURE 22. Aluminum Specimen 10, Entrance Hole Damage.
Torque on Impact = 16,350 in.-lb,
Residual Strength = 22,000 in.-lb.

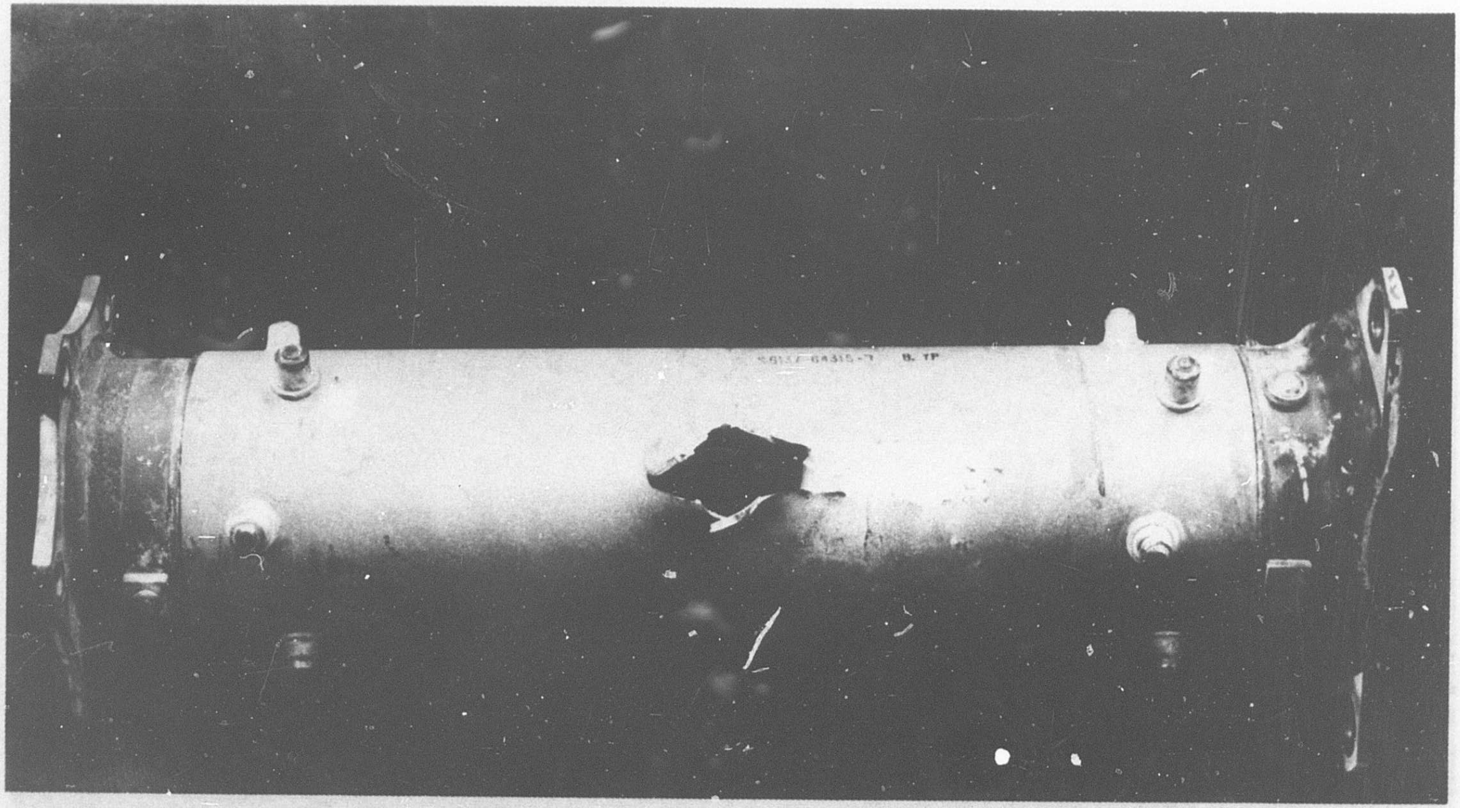


Figure 23. Aluminum Specimen 10, Exit Hole Damage. Torque on Impact = 16,350 in.-lb, Residual Strength = 22,000 in.-lb.